Coherence time and statistical properties of the GPS signal scattered off the ocean surface and their impact on the accuracy of remote sensing of sea surface topography and winds

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Abstract - **A GPS transmitter-receiver pair forms a bistatic radar for ocean remote sensing when the receiving platform carries a down-looking antenna capable of collecting the GPS signal scattered off the ocean surface. The average received power versus time is derived as a function of viewing geometry, system parameters and an ocean state. This waveform is crucial for the derivation of the sea surface topography (from its leading edge) or wind speed and direction (from its trailing edge). In predicting the accuracy of either measurement it is important to understand how accurately the average power can be determined in practical situations. This starts with the determination of the coherence time of the scattering, over which the received signal can be integrated for optimal signal to noise ratio. Additionally, the real signal is affected by self-noise which introduces variability from one sample to another. This work examines the coherence properties of the modeled received power as a function of sea state and scattering geometry. In particular the coherence time variability between leading and trailing edges is addressed, and its impact on the accuracy of either sea surface topography or wind speed and direction measurements is addressed. In particular, having determined the integration time necessary to produce independent samples, the incoherent summation time required for a given measurement accuracy is derived. Furthermore, the lag-to-lag correlation is addressed, leading to a covariance analysis formulation for the formal error in height retrieval.**

I. INTRODUCTION

The Global Positioning System (GPS), which was first conceived and built for the purpose of navigation, has been successfully used as an Earth remote sensing tool in the past fifteen years for solid earth and atmospheric probing. More recently, the possibility to utilize the GPS signals scattered off the ocean and sensed by an air- or space-borne receiver in a bistatic radar geometry, as a means of doing altimetry and scatterometry. The advantage of GPS is twofold: the transmitted signal is global and is present at all times and in all weather conditions and the receiver technology is rather inexpensive, compared to alternative remote sensing systems. To take advantage of this new possible measurement one needs to understand the characteristics of the received signal and how they relate to the ocean properties such as sea surface height and winds.

The fundamental process being observed is the bistatic scattering from the rough ocean surface, driven by winds. When the GPS signal impinges on the ocean it scatters in all directions, with maximum contribution along the forward scattering direction about the specular reflection point. At any given observation time, one specific area of the ocean forming an ellipse or an elliptical annulus stretching between transmitter and receiver contributes to the overall received power, through a collection of scattering contributions with varying local scattering geometries. As the observation time increases the annulus axes become larger and larger, thus sensing areas of the ocean surface moving further away from the specular reflection point. By combining the surface contributions that arrive at the receiving antenna at the same time, the impact of the ocean state and the geometry and system parameters on the received power waveform is studied.

The GPS transmits a carrier at two L-band frequencies modulated by one or more pseudo-random code sequences. When processing the received data stream, one usually chooses a coherent integration time during which cross correlations between the data and a code replica, or expected signal, are performed over a range of values for the delay and the Doppler to maximize the operation output. Fixing the integration time T_i is equivalent to setting a bandwidth in the receiver, meaning that oscillations (Doppler shifts) higher than the threshold set by the reciprocal of the integration time, are not resolved. This process amounts to a spatial filtering. The choice of integration time is commensurate to the coherence of the process being observed, in this case bistatic ocean scattering from surfaces large compared to the signal wavelength. Choosing a very small coherent integration time will not allow to build up the correlator output to its full potential, whereas integrating for too long will not improve over incoherent summation of independent samples.

This paper discusses the coherence properties of the received signal as a function of the observation time and hence of the location on the received waveform (leading edge versus trailing edge) and examines its impact on the accuracy of the sea surface parameters obtained from it, i.e. sea surface height from the leading edge and wind vector from the trailing edge.

II. POWER SPECTRUM OF RECEIVED POWER

The de-spread instantaneous signal is defined in [1] as:

$$Y(t_0,\tau) = \int_0^{T_i} a(t_0 + t')u(t_0 + t' + \tau)\exp(2\pi i f_c t')dt'. \quad (1)$$

where $u(t)$ is the complex amplitude of the scattered signal (the voltage) which is acquired directly by the receiver by cross correlation with a replica expressed as a coherent integration in T_i. In (1) t_0 is the time at which a sample is generated while τ is a lag value spanning the observed waveform. A complex correlation function in Y() can be formed by shifting the sample time, and by taking its Fourier transform the power spectrum is obtained:

$$W_Y(f,\tau) = \int \frac{|\Re|^2 q^4}{4R_0^2 R^2 q_z^4} P_v\left(-\frac{\vec{q}_\perp}{q_z}\right)\Lambda^2[\tau - (R_0 + R)/c]\cdot\left|S(f_D - f_c + f_0)\right|^2$$
$$\times\,\delta[(\vec{v}_R\cdot\vec{n} - \vec{v}_T\cdot\vec{m})/\lambda + f - f_0]d^2\eta. \quad (2)$$

where the notation is consistent with [1] and the explicit dependence on sea state is through the pdf of slopes P_v. This equation states that at any lag the existing spectral components span the region that will annihilate the argument

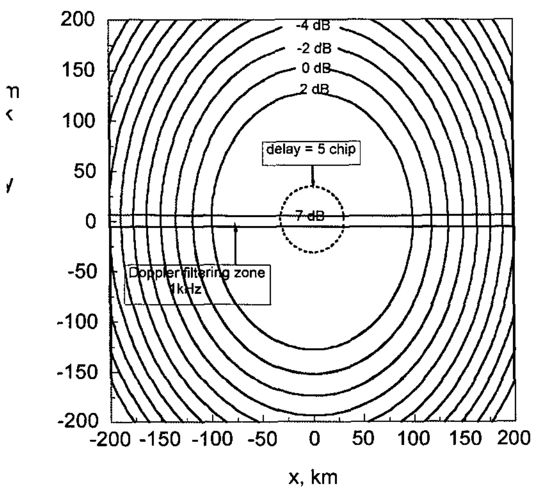

Figure 1. Geometry of the surface scattering.

of the delta function and their amplitude is modulated by the aggregate of scattering reflection coefficients. Hence, we can extract the coherence time from these spectra to optimally choose the integration time. In the above derivation we assume to be dealing with mean values. Real data are affected by noise so averages must be taken over many samples. The next step is determining the number of samples needed to produce an incoherent average corresponding to a specified accuracy.

Spatial zones that correspond to integrand functions in Eq.(2) are shown in Figure 1. The case is considered here of a satellite receiver at 400 km altitude, with 60° elevation angle for the GPS transmitter, Ti = 1 ms integration time and U = 8 wind speed. We performed calculations of the integral in Eq.(2) and obtained the normalized power spectra of the GPS reflected signal for various time lags. Results are presented in Figure 2. One can see that the width of spectra grows for the leading edge and peak area (lags from –0.75 to 0 chip).

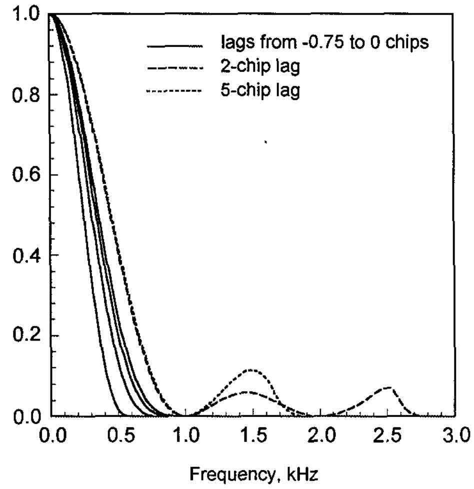

Figure 2. Power spectra at various time lags.

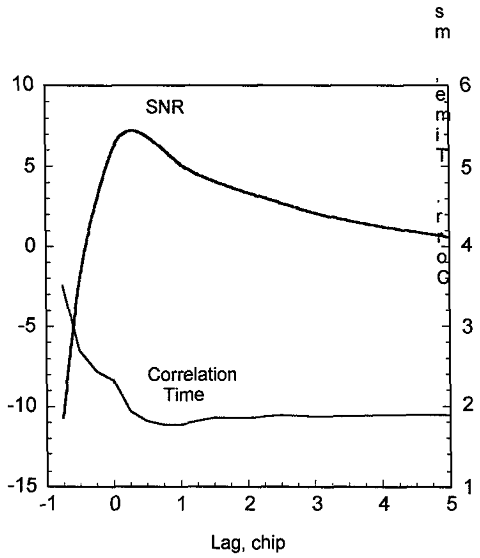

Figure 3. Modeled GPS reflected waveform and corresponding correlation time for various lags.

For the trailing edge the width of the main spectral lobe saturates at some level, however, minor lobes occur at higher frequencies. This is a result of having two separate zones of contributions at larger lags (see Figure 1).

In Figure 3 we presented a dependence of the correlation time of the scattered signal versus lag. The correlation time obtained as an inverse value to the spectral width at 1/e level. At the same plot, the power SNR waveform is shown for a comparison.

III. Statistics of Received Power

In practice the acquired signal is affected by noise in the form:

$$v(t) = u(t) + n(t) \tag{3}$$

where $u(t)$has been introduced in (1), and $n(t)$ is the complex amplitude of the additive noise. We assume that $u(t)$and $n(t)$ are two uncorrelated, stationary random processes, both obey circular Gaussian statistics and have different time scales, and different variances $\sigma_1^2 \equiv \sigma_{\mathrm{Re}u}^2 \equiv \sigma_{\mathrm{Im}u}^2$, $\sigma_2^2 \equiv \sigma_{\mathrm{Re}n}^2 \equiv \sigma_{\mathrm{Im}n}^2$, both with zero means. Usually, the Gaussian statistics for $u(t)$ is justified because the signal at the antenna is formed by contributions from a large number of independent surface scatterers. For the general ocean conditions, there is no coherent component in the signal, although a strong surface scattering in the diffusive regime is present. Fluctuations of $u(t)$ generate multiplicative, self-noise, which disappears together with transmitted signal, whereas fluctuations of $n(t)$ generate additive, background noise (i.e., thermal noise or shot noise). It could be shown (see, e. g., [2]) that the statistics of the combined signal $v(t)$is also complex Gaussian with the variance given by the sum of the variances of the individual random processes. In a real situation we deal with values averaged over some numbers of samples, or over a finite time interval in order to improve signal-to-noise ratio. Since the number of samples, or the averaging time, is finite the procedure doesn't lead to constant time-independent values. These sample-averaged values are still random quantities and need to be described in statistical terms. Only in the limit of infinite number of samples the result will coincide with the theoretical mean, or expectation value given by theoretical models. The issue of the residual fluctuations of the sample-averaged GPS reflected power is a very important issue for the retrieval algorithms, either for sea surface heights or winds. In particular, if the variance of the sample-averaged power at some delay bin exceeds the difference between powers obtained for two different wind speeds (or wind directions), then these two winds cannot be distinguished, thus limiting the accuracy. Note that at the same time the indetermination in wind speed also results in indetermination of sea surface height, since the point on the leading edge corresponding to the specular reflection is wind speed dependent. An additional averaging would be required for a reduction of the variance below a desired level.

IV. Estimation of a Required Sample Numbers for Altimetry and Wind Retrieval.

Using approach similar to one described in [3] one can estimate the number of required samples in order to achieve a desired accuracy of height an wind measurements. It is based on r.m.s. SNR for the partially averaged power expressed in terms of the power SNR, integration time, and the correlation time for the scattered signal. Results are shown in Figure 4.

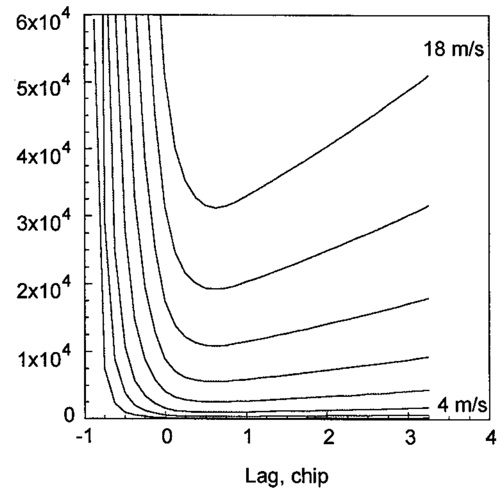

Figure 4. Number of samples needed to resolve winds as a function of the time lag.

One can see that the number of samples grows with wind speed. Different parts of the waveform require different number of samples to achieve the same accuracy.

Acknowledgment

This work was performed in part at the Jet Propulsion Laboratory/Caltech under Contract with the National Aeronautics and Space Administration. Part of the work was performed at NOAA/ETL, under subcontract to JPL.

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